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6. AUTHOR(S)
Warren B. Powell

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Department of Civil Engineering & Operations Research
PRINCETON UNIVERSITY
Princeton, NJ 08544

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Neal Glassman
AFOSR NM
110 Duncan Avenue, Suite B 115
Bolling AFB, Washington, DC 20332-0001

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The project is developing control technologies for large, complex operational problems. These technologies are intended for both real-time and tactical planning, and can be imbedded in larger simulation models for strategic planning purposes. In a simulation setting, the techniques provide optimization capabilities within strategic planning models, replacing the simple rules and heuristics most commonly used in simulation models. By contrast, they offer much more flexibility than classical linear programming models. In a real-time setting, the optimization methods provide tremendous flexibility and fast response with relatively easy diagnostics. The tools are especially robust with respect to the uncertainties that are intrinsic to any real-time setting. In addition to the development of new optimization techniques, the research encompasses heuristic learning, graphical diagnostics, a modular object library, and a flexible simulation architecture that can be used to test and evaluate different optimization techniques, as well as perform detailed simulations for strategic planning purposes.

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Final Report:

Stochastic Set Partitioning Methods for Operational Planning of Aircraft

Principal Investigator:

Warren B. Powell

Grant: F49620-93-1-0098

May, 1996

Princeton University

Department of Civil Engineering and Operations Research

Princeton, NJ 08544

powell@princeton.edu

Abstract

The project is developing control technologies for large, complex operational problems. These technologies are intended both for real-time and tactical planning, and can be imbedded in larger simulation models for strategic planning purposes. In a simulation setting, the techniques provide optimization capabilities within strategic planning models, replacing the simple rules and heuristics most commonly used in simulation models. By contrast, they offer much more flexibility than classical linear programming models. In a real-time setting, the optimization methods provide tremendous flexibility and fast response with relatively easy diagnostics. The tools are especially robust with respect to the uncertainties that are intrinsic to any real-time setting. In addition to the development of new optimization techniques, the research encompasses heuristic learning, graphical diagnostics, a modular object library, and a flexible simulation architecture that can be used to test and evaluate different optimization techniques, as well as perform detailed simulations for strategic planning purposes.

1. Objectives

We are developing technologies for real-time control of complex operational systems arising in transportation and logistics, using the Airlift Mobility Command as a candidate application. Our broad goal is the development of optimization models and algorithms for real-time and strategic planning. Specific intermediate goals are:

Task 1) Development of a general taxonomy for covering a broad class of operational problems arising in transportation. Our goal is a taxonomy broad enough to encompass problems within AMC, but which also identifies opportunities for parallel applications in the civilian sector.

Task 2) Development of a flexible mathematical notation that captures the structure of this class of problems. Our goal here is a simple, flexible notation that can easily reflect a broad range of complex operational issues (such as those studied by AMC using MASS) and yet still retain the structure of the problem so that we can optimize it (in contrast with MASS, which is a pure simulation).

Task 3) Development of a flexible software object library that allows us to execute the equations developed with the notation system. Our goal here is an architecture that easily handles a high level of complex operational issues yet maintains a separation between the optimization algorithm and the underlying model.

Task 4) Development of a simulation environment that will allow us to easily test and compare different optimization models and algorithms in a simulated real-time environment.

2. Status of effort

Our progress in each of the tasks listed above:

Task 1) We have developed an initial "prototype" taxonomy, and we are in the process of classifying the problems addressed by AMC within the taxonomy.

Task 2) We have developed a very flexible mathematical notation that is very easy to understand and apply. At this point, it covers a difficult class of heterogeneous, dynamic resource allocation problems, but does not yet have the full generality required by our taxonomy.

Task 3) We designed a highly flexible software architecture around our mathematical notation, and we are testing its application simultaneously to several complex operational settings. It is approximately 60 percent complete.

Task 4) We have a prototype simulation architecture that handles different components of a complex simulation using a modular, parallel architecture. The goal is to keep simulation logic separate from optimization logic, allowing us to test alternative optimization models and algorithms. An initial version of the system is running now.

By the end of 1995, we will be able to describe (in English), model (in mathematics), program (using object modules) and test (using our simulation environment) a broad class of optimization models and algorithms for a relatively general class of dynamic resource allocation problems. Finally, we use relationships with groups such as the Airlift Mobility Command to perform field implementation and testing.

3. Accomplishments/new findings

1. **Dynamic routing and scheduling:** We have developed an approximation algorithm for dynamically scheduling drivers and vehicles over multiple tasks using a novel parallel dynamic programming algorithm. The algorithm can optimize the routing and scheduling of drivers over multiple task tours, handling complex work rules and service constraints. The system runs in real-time, reoptimizing tours for 500 drivers in a few seconds.

2. **Dynamic fleet management:** We have a new optimal control procedure for large scale dynamic fleet management problem. Commonly tackled by the research community as a multicommodity network flow problem, we can optimize the allocation of multiple vehicle types over thousands of tasks, handling narrow or wide time windows, and providing integer solutions. Solution quality is within 3 percent of a linear relaxation (noninteger solution), with run times that are up to 100 times faster for large problems (and thousands of times faster for large problems with long planning horizons). The system can be run in real-time.

3. **Centralized vs. decentralized control of resource allocation problems:** We show that we can optimize the distribution of reusable resources (containers, aircraft) over space and time using a decentralized strategy and achieve results within 2-3 percent of a global, central control strategy.

4. **Optimization of stochastic dynamic networks:** We have found a way to provide a fast, convergent algorithm for optimizing resources over two-stage networks under uncertainty, without losing the underlying network structure. Other techniques lose the network structure, and the integrality problems that often come with networks. Our new method is a mathematically convergent algorithm, but easily produces integer solutions when the underlying problem is a network.

5. **Adaptive estimation of daily demands:** We have developed an adaptive smoothing algorithm for estimating daily demands, accounting for complex calendar effects (day of week, week of month, season, holidays, etc.)

6. **Dynamic optimization of complex, multiattribute resource allocation problems:** We are in the initial stages of testing a flexible, general purpose optimization system of large scale, dynamic resource allocation problems with complex attributes. A special modeling language and software architecture allows flexible specification of attributes and the evolution of these attributes over time. A dynamic programming approximation provides the framework for optimizing these systems. A variety of forecasting uncertainties are easily incorporated. Initial testing suggests solutions are of very high quality.

4. Personnel supported

Faculty:

- Professor Warren B. Powell
- Professor Robert Vanderbei

Graduate students:

- Greg Godfrey
- Zhi-Long Chen
- Tassio Carvalho

Undergraduates

- Jacob Pollack
- Paul Hanson

5. Publications (10/1/94 - 9/30/95)

5.1. Submitted but not yet accepted:

1 "Adaptive Estimation of Daily Demand with Complex Calendar Effects," submitted to *Management Science* (with Greg Godfrey).

2 "The Convergence of Hybrid Stochastic Gradient Methods in Stochastic Programming, with an Application to Dynamic Networks with Random Arc Capacities," submitted to Operations Research (with Raymond K.L. Cheung).

3 "On Bertsekas' Small-Label-First Strategy," submitted to *Networks.* (with Zhi-Long Chen).

4 "Dynamic Control of Logistics Queueing Networks for Large Scale Fleet Management," submitted to Transportation Science (with Tassio Carvalho).

5 "A Decomposition Approach for a Parallel Machine Just-In-Time Scheduling Problem," submitted to Naval Research Logistics Quarterly (with Zhi-Long Chen).

6 "An Exact Solution Algorithm for Parallel Machine Weighted Number of Jobs Problems," submitted to ORSA Journal of Computing (with Zhi-Long Chen).

7 "Solving Parallel Machine Total Weighted Completion Time Problems by Column Generation," submitted to Operations Research (with Zhi-Long Chen).

8 "Dynamic Control of Multicommodity Network Flows," ..submitted to European Journal of Operations Research.(with Tassio Carvalho).

9 "Real-Time Optimization of Containers and Flatcars for Intermodal Operations," submitted to Transportation Science (with Tassio Carvalho)

10 "A Multiplier Adjustment Method for Dynamic Resource Allocation Problems," submitted to Operations Research (with Tassio Carvalho)

11 "An Optimal Control Formulation of Large-Scale Multiclass Machine Scheduling Problems," submitted to Proceedings of Network Optimization Conference in Gainesville, 1996.

5.2. Accepted but not yet published:

1 "A Stochastic Formulation of the Dynamic Assignment Problem, with an Application to Truckload Motor Carriers", Transportation Science. To appear.

2 "An Approximate Algorithm for the Dynamic Assignment Problem," Proceedings (refereed) of TRISTAN, 1994 (with Derek Gittoes). To appear.

3 "Toward a Unified Framework for Real-Time Logistics Control," *Military Journal of Operations Research.* To appear.

4 "An Algorithm for Multistage Dynamic Networks with Random Arc Capacities, with an Application to Dynamic Fleet Management," *Operations Research*, (with R. K.-M. Cheung). To appear.

5 "Finding the Yellow Brick Road," *Interfaces,* to appear. (with Don Mayoras)

6 "An Improved Polynomial Bound for the Expected Network Recourse Function" Annals of Operations Research on Stochastic Programming, (J. Higle and S. Sen, eds) (with L. Frantzeskakis). To appear.

7 "An Approximate Labeling Algorithm for the Dynamic Assignment Problem," Advanced Methods in Transportation Analysis, (L. Bianco, P. Toth, M. Bielli, eds.), Springer-Verlag, June, 1996 (with D. Gittoes). To appear.

5.3. Published:

1 "Network Recourse Decomposition Method for Dynamic Networks with Random Arc Capacities," *Networks*, pp. 369-384, 1994. (with. R. K.-M. Cheung).

2 "Stochastic Programs over Trees with Random Arc Capacities," *Networks*, Vol. 24, pp. 161-175 (1994). (with R. K.-M. Cheung).

3 "Subgradient Optimization for the Service Network Design Problem," *Transportation Science*, Vol. 28, No. 3, pp. 256-272, 1994. (with J. M. Farvolden).

4 "Stochastic and Dynamic Networks and Routing," to appear in *Handbook in Operations Research and Management Science: Network Routing*, (M.O. Ball, T.L. Magnanti, C.L. Monma and G.L. Nemhauser, eds.), pp. 141-295 (1995) (with A.R. Odoni and P. Jaillet).

5 "Dynamic Fleet Management as a Logistics Queueing Network," Annals of Operations Research on Transportation (G. Laporte and M. Gendreau, eds.) *Annals of Operations Research on Transportation*, Vol. 6, pp. 165--188 (1995) (with T. Carvalho, G. Godfrey and H Simao).

6 "Models and Algorithms for Distribution Problems with Uncertain Demands," *Transportation Science*, Vol. 30, No. 1, pp. 43-59 (with R. K.-M. Cheung).

5.4 Technical reports

1 "A Generalized Threshold Algorithm for the Shortest Path Problem with Time Windows," submitted to Journal on Computing. (with Zhi-Long Chen).

6. Interactions/transitions

6.1. Participation/presentations at meetings, conferences, etc.

Invited talks:

1 "Real-Time Control of Logistics: Models and Algorithms," Conference sponsored by the Office of Naval Research, George Mason University, 1995.

2 "Dynamic Models in Transportation: Issues and Applications", Keynote address to the Rail Special Interest Group, University of Pennsylvania, Philadelphia, 1995.

3 "Autonomous Control of Logistics Systems," The Northwestern University Manufacturing Management Symposium Series, Evanston, Illinois, 1995.

4 "Optimization Models for Real-Time Logistics," invited tutorial presented at the Mathematical Programming Symposium, Ann Arbor, Michigan, 1994.

5 "Dynamic Models in Transportation and Logistics," invited plenary presentation at TRISTAN Symposium, Capris, Italy, 1994.

6 "Stochastic Programming for Dynamic Fleet Management," University of Montreal, Montreal, Canada, 1994.

7 "Dynamic Models in Transportation and Logistics," Department of Industrial Engineering, Iowa State University, Ames, Iowa, 1994.

Conferences: Numerous talks at the biannual INFORMS meetings.

6.2. Consultative and advisory functions

I regularly visit with Alan Whisman and Tony Waisanen at the Airlift Mobility Command in St. Louis. I am collaborating with them on an object-oriented simulation environment that might replace MASS and improve their analysis capabilities.

6.3. Transitions

A major thrust of my research program is the development of general purpose analysis tools for dynamic resource management problems. This approach allows us to identify opportunities for applications of our developments in different arenas, although our focus is entirely on transportation problems similar to those faced by AMC.

Specific transitions that have occurred include:

1 Transition: Implementation of our dynamic assignment algorithm, LASER, for real-time routing and scheduling of short-haul drayage movements (these are movements of intermodal freight between a rail terminal and a customer location).

Recipient: Triple Crown Services, Inc.

2 Transition: We have applied our optimal control methodology based on our new "logistics queueing network" (LQN) formulation, to the management of their intermodal flatcar fleet.

Recipient: Norfolk Southern Railroad

3 Transition: We have applied our optimal control methodology to the management of the linehaul network for LTL motor carriers. These problems involve tactical planning of over 10,000 drivers.

Recipient: Yellow Freight System, Inc.

4. Transition: We have adapted our multiattribute labeling algorithm to handle real-time load planning for truckload motor carriers.

Recipient: Burlington Motor Carriers

7. New discoveries, inventions or patent disclosures

I have made five specific disclosures to the Princeton University patent office. These disclosures are being evaluated for patentability.

- Adaptive estimation of daily freight demand with complex calendar effects - This algorithm handles daily demand forecasting, and can reflect a variety of day of calendar effects, including day of week, week of month, month of year and holidays (including floating holidays).
- A labeling algorithm for routing drivers with general attribute vectors to describe drivers and tasks, and complex work rules. The algorithm, called LASER, can handle real-time routing and scheduling of systems with thousands of drivers, providing response times in the 5-10 second range (on low end workstations).
- We have invented a new modeling approach for large scale dynamic resource allocation problems. The approach uses a new formulation we call "logistics queueing networks." We have tested the logic on problems with 2,000 (homogeneous) vehicles serving 10,000 loads over a 10 day planning horizon, where every load can be served within a specified time window. The logic produces integer solutions within 2-4 percent of a linear programming relaxation. The most important attribute of the methodology is the ease with which it handles much more complex problems. For example, it easily handles multiple vehicle types.

8. Honors/awards

Recipient of the IEEE Award for the best paper on land transportation, awarded by the Vehicular Technology Society of IEEE.